Temperature change and urbanisation in a multi-nucleated megacity: China's Pearl River Delta

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Abstract

This paper investigates urbanisation and temperature indices, over four decades in a multi-nucleated megacity, China's Pearl River Delta (PRD). Daily mean minimum, maximum and mean temperatures (T_{min}, T_{max} and T_{mean}) have increased considerably above background warming rates. However, only weak to moderate relationships are observed between trends in local urban surface area surrounding climatic stations, and T_{min} used as a proxy for UHI development. While 5 out of 21 stations with high increase in both T_{min} and degree of urbanisation, showed moderate relationship (R=0.51), another 8 stations with low urbanisation showed significant increase in T_{min}. This suggests warming from factors other than local urban development on T_{min}. Since PRD contains 123 cities over 1 million population, and a semi-continuous urbanised area due to merging of urban centres, a regional heat island circulation, or heat dome model is invoked. The observed increase in T_{max} above background warming rates for 14 stations, is more difficult to explain as T_{max} is not generally affected by urbanisation. This is attributed to high surface energy flux in the afternoon, and anthropogenic energy use in dense urban districts. The regional heat dome circulation over PRD suggests local temperatures will increase further, even without further local developments.

Key words: Urban Heat Island, daily minimum temperature, climate warming, urbanisation, urban heat dome, Pearl River Delta

1. Introduction

Urban Heat Islands (UHIs) have been recognised as influencing minimum air temperatures in cities, and are noted in IPCC's Fifth Assessment Report for their possible impact on global warming. As cities increase in size and built density, especially in developing countries, these impacts would be expected to increase. The emergence of megacities in recent decades changes the traditional concept of the UHI, as multi-nucleated city forms are under-studied in terms of their overall climatic impacts. The Pearl River Delta region of southern China has developed from farmland and small villages before 1985, to become the world's largest megacity today. The economic boom of the past 40 years, has seen vast areas of farmland developed into urban areas (Chen et al. 2006; Dou and Chen, 2017) and the problem of environmental degradation, has become a major concern here, as throughout China. The population of the PRD urban area grew from 27 million in 2000 to an astounding 42 million in 2010. Today, the PRD region contains eight megacities with populations over 10 m and 123 cities with between 1 and 10m (World Bank Group, 2015). The PRD consists of nine municipalities, namely Guangzhou, Shenzhen, Dongguan, Foshan, Jiangmen, Zhongshan, Zhuhai, Huizhou and Zhaoqing. These cities began to merge into a single megacity in the 2000-2010 decade (Figure 1), and if considered as a single entity, the PRD overtook Tokyo as the world's largest megacity in both size and population. The urbanised area is approximately 52,000 km^2 (based on DMSP nightlights imagery in 2012). In terms of urban form it is unique in its immense size as well as multi-nucleated structure.

Despite the PRD's economic success its sub-tropical climate, with an annual mean temperature of 21 to 23°C, and rainfall peak during the hot summer season, makes the climate uncomfortable during several months. This is exacerbated by low wind speeds of 2-3 m/sec in urban areas compared with regional winds of 6-7 m/sec (Hong Kong Observatory, 2019). Currently four months of the year in PRD have daily maximum temperatures and relative humidity equating to severe stress on ASHRAE's human thermal comfort index (ASHRAEA, 2010). The extent to which urbanisation alone has influenced temperatures in PRD through the formation of an urban heat island, is the focus of this study. In addition, we aim to examine whether the urban heat island (UHI) structure and characteristics are different from those observed elsewhere, due to the uniqueness of size and urban form of this multi-nucleated city.

Since urban heat islands are formed when urban structures release daytime heat more slowly than rural areas, and the greatest difference between these cooling rates may be in the early morning around 4-5am, the urban heat island is recognised as a night-time phenomenon (Figure 2). For example, Hong Kong's urban climatic station (HKO) (Figure 2) undergoes a much reduced diurnal temperature fluctuation due to reduced night-time cooling than does Hong Kong's rural station (TKL) due to heat retention by built structures. Therefore, as the UHI reduces cooling, the best measure of urban heat island magnitude is the daily minimum temperature (T_{min}). The graph also indicates that rural daily maximum temperatures (T_{max}) may sometimes exceed those in urban areas, which is attributed to building shadow and street canyon effects during the hottest time of day in urban areas compared to more open and exposed rural surfaces.

IPCC's Fifth Assessment Report (AR5) (2014) states that there is a large amount of evidence that as well as increase in mean land surface air temperatures (T_{mean}), both T_{max} and T_{min} have also increased at over 0.1°C per decade since the 1950s. For the period 1950 to 2010 they cite Rohde et al (2013). We therefore use estimates from Rohde et al (2013) who amalgamated data from 14 databases and over 14.4 million climate stations which give the maximum and minimum daily temperatures as having increased by 0.91 and 1.06 °C from the 1950s to 2010. This will be referred to as 'background warming', for comparison with data for the PRD stations examined in this study. Since our study period covers only 4 decades Rohde et al's these estimates are likely to be on the high side.
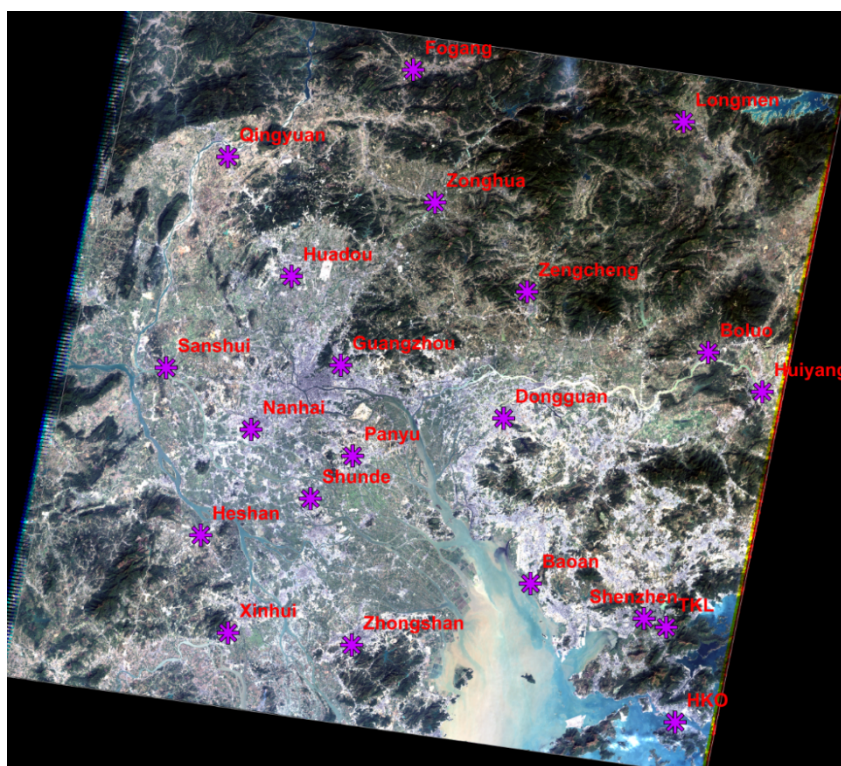
Figure 1. Location of the 21 climate stations used in the study, superimposed on a Landsat image of the Pearl River Delta region, Path 122 Row 44, of 12th December, 2003.
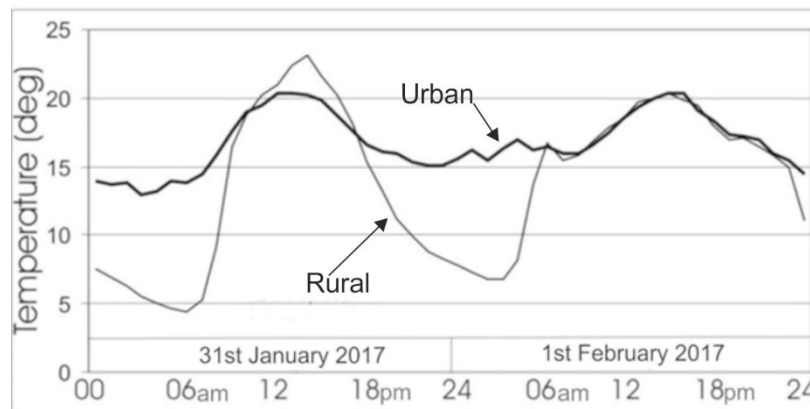

Figure 2. Hourly air temperatures at an urban climate station in Hong Kong (Hong Kong Observatory (HKO)) and a rural station in Hong Kong (Ta Kwu Ling (TKL)) over a typical 48-hour period. Thick line=HKO, thin line = TKL. Data from Climatological Information Services, Hong Kong Observatory.

1.1 Objectives
We examine temperature data for 21 climate stations in the Pearl River Delta region of China, over 4 decades, to determine
  (i)   The influence of urban development in the Pearl River Delta on local and regional temperature indices, over four decades: 1975 to 2014
  (ii)   The spatial extent and structure of the UHI across a multi-nucleated megacity

2. Methodology
A Region of Interest (ROI) of approximately 211 km x 201 km was selected for this study which includes nine municipalities in Guangdong Province as well as the Hong Kong and Macau Special Administrative Regions (Figure 1). This area is covered by Landsat imagery of Path 122 Row 44 (Figure 1) and the study period was defined according to availability of cloud-free Landsat images from 1975 to 2014. Daily, monthly and annual air temperature data from 21 climate stations representing urban areas across the PRD were also available for this period. The only non-urban station is Hong Kong's Ta Kwu Ling (TKL), and data for TKL are only available since 1987. Linear fitting of the daily average T_{max}, T_{min} and T_{mean} over all years of the study 1975 to 2014, was performed, with a small p value showing all trends to be significant.

The Landsat images were used for deriving the extent of impervious surfaces from the visible wavelength images. Impervious surface areas (ISAs), representing the degree of urbanisation, were retrieved from the visible wavelength images as follows: first the images were classified using object-based multi-resolution segmentation in eCognition, then two indices, the

Normalised Difference Bareness Index (Kawamura et al, 1996) and the Normalised Difference Built-Up Index (Chen et al, 2006), were applied to extract impervious surfaces (ISAs). The ISA images were validated for areas within a 5 km diameter surrounding each of the 20 climate stations, using a 2014 digital Land Use map of the PRD from the Lands Department of Hong Kong. Average accuracy for all stations was found to be 92%. Three buffer rings surrounding each climate station were created with diameter of 1km, 3km and 5km (Figure 3), and the changes in ISA within each ring, over the study period, were calculated. In addition to built-up area, it is likely that built volume ie. the 3-dimensional aspect of a city contributes to daytime heat retention, but as no historical and/or open source data are available for PRD e.g. the digital surface model (DSM) for calculation of building height, the 3D aspect could not be examined.
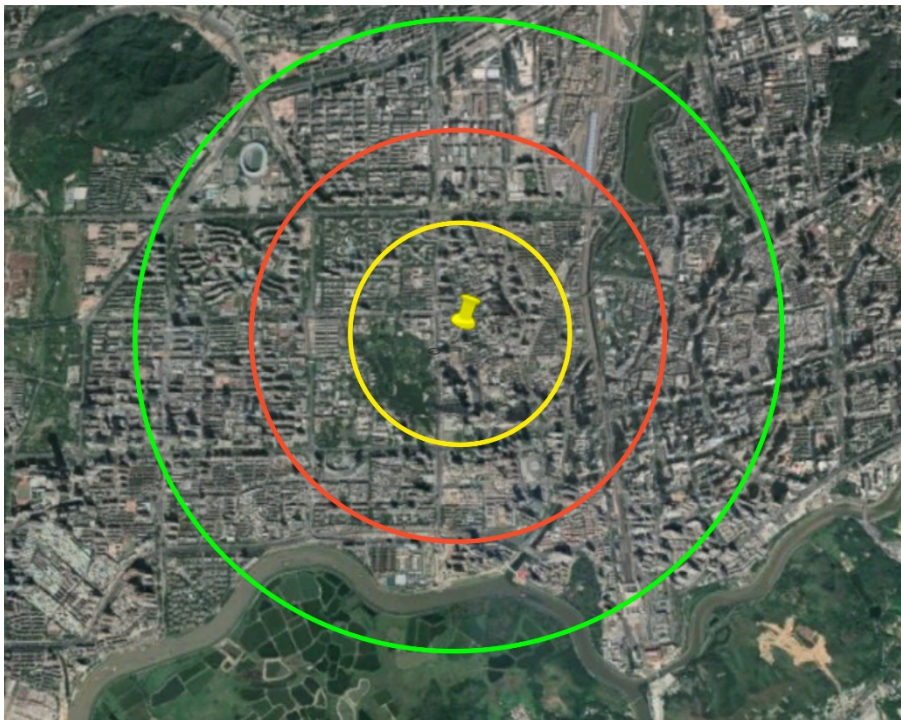

Figure 3. Buffer rings of 1, 3 and 5 km diameter surrounding Shenzhen climate station. The river at south of the image constitutes the border between Hong Kong and mainland China.

3. Results

3.1 Temperature trends

Table 1 represents the change in mean T_{max}, T_{min} and T_{mean} at each station over the 40-year period from linear fitting. Figure 4a shows that for T_{min}, 13 out of 21 stations in PRD have exceeded the global background warming of approximately 1.06 °C (Rohde et al, 2013), and five of these recorded more than 0.5 °C above the background increase. Shenzhen in particular saw a very high warming rate of 2.41 °C for T_{min} over the 40-year period. The average change in T_{min} for all stations, of 1.23 °C, was higher than for T_{mean}, and T_{max}, which increased by warming, of 0.09 and 1.18°C respectively. These results suggest a significant urban warming influence over the PRD, as the UHI has greatest influence on minimum air temperatures, which rise due to night-time heat retention by urban structures. It is interesting to note that T_{max} has also increased significantly above background rates (Table 1 and Figure 4b), although urbanisation is not typically associated with such increases. In fact 14 out of 21

stations exceeded the background warming rate of 0.9 °C for T_{max}, and seven of these by more than 0.5 °C. Generally those stations which exceeded for T_{min} also exceeded for T_{max}.

Figure 5a indicates that Hong Kong's HKO station had much higher T_{min} (by 1.5 °C) than any other station in 1975. In fact Hong Kong's urban station at the Hong Kong Observatory (HKO) already had 30% of ISA within the 1 km buffer ring in 1975, and would already be subject to UHI effects with reduced cooling at night. Because of this, HKO shows the least urban growth among all stations over the following 40 years. On the other hand, HKO's T_{max} in 1975 was one of the lowest (Figure 5b), probably due to shadow effects in urban areas during the daytime compared to the rural situation of the other PRD stations in 1975. Correspondingly, neither T_{min} nor T_{max} ~~increases~~ at HKO exceeded the background temperature increases of 1.09 °C and 0.90 °C respectively, over the 40-year study period (Figure 4 and Table 1).

Station	T_{min}	T_{mean}	T_{max}	% ISA 1km	% ISA 3km	% ISA 5km
Baoan	1.42	1.35	1.45	29 *(29)*	13 *(15)*	16 *(17)*
Boluo	1.87	1.34	1.22	80 *(80)*	31 *(42)*	11 *(24)*
Dongguan	1,13	1.09	0.77	94 *(94)*	57 *(64)*	50 *(57)*
Fogang	1.02	0.80	0.78	85 *(85)*	35 *(44)*	8 *(21)*
Guangzhou	0.51	0.55	0.96	55 *(55)*	48 *(50)*	42 *(46)*
Heshan	1.55	1.72	2.00	59 (60)	40 (46)	20 (32)
HKO	0.88	0.71	0.39	32 (61)	32 (43)	9 (34)
Huadou	1.41	1.47	1.60	79 (86)	43 (59)	32 (45)
Huiyang	1.08	1.11	1.20	69 (69)	47 (50)	26 (35)
Longmen	0.26	0.31	0.60	5 *(5)*	7 *(7)*	8 *(9)*
Nanhai	1.40	1.59	1.87	69 (69)	59 (63)	35 (56)
Panyu	1.49	1.66	2.04	90 (89)	56 (72)	39 (54)
Qingyuan	0.54	0.61	1.00	66 (66)	35 (39)	17 (25)
Sanshui	1.19	1.20	1.27	79 (79)	53 (57)	17 (32)
Shenzhen	2.41	0.54	0.55	79 (71)	59 (61)	52 (57)
Shunde	2.26	2.12	1.94	99 (99)	45 (61)	25 (42)
*TKL	0.2	0.13	0.37	23 (23)	14 (15)	7 (10)
Xinhui	1.73	0.31	0.75	51 (51)	29 (46)	25 (37)
Zengcheng	0.56	0.60	1.38	21 (20)	7 (11)	5 (8)
Zhongshan	1.61	1.50	1.49	35 (34)	26 (27)	31 (31)
Zonghua	-0.14	0.26	1.38	64 (94)	40 (53)	18 (30)
AVERAGE	**1.23**	**1.09**	**1.18**	**60 (63)**	**37 (44)**	**23 *(33)***

Table 1. Changes in absolute T_{min}, T_{mean} and T_{max} (°C), and percentage change in ISA from 1975 to 2014 (number in brackets represents percentage ISA in 2014). *TKL started temperature recording in 1989.
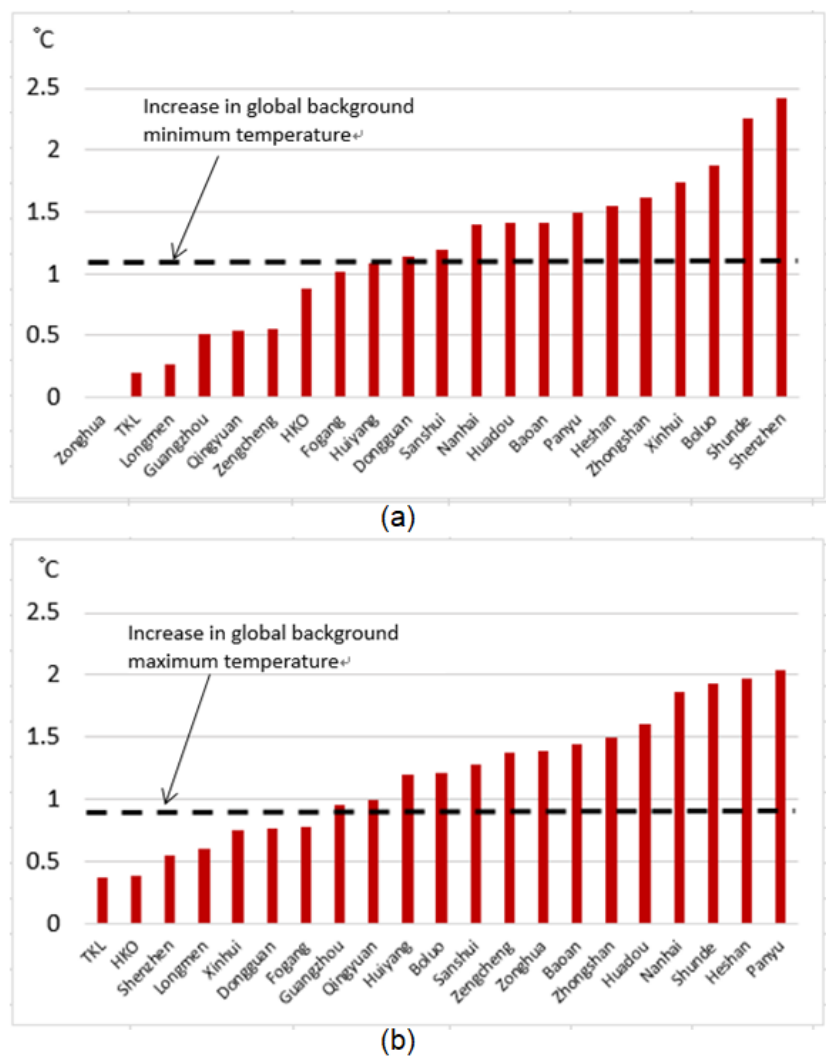
°C

(a)

(b)

Figure 4. Increase in station T_{min} (a) and T_{max} (b) compared with global background increase (Rohde et al, 2013) over 40-year study period, sorted by amount of increase
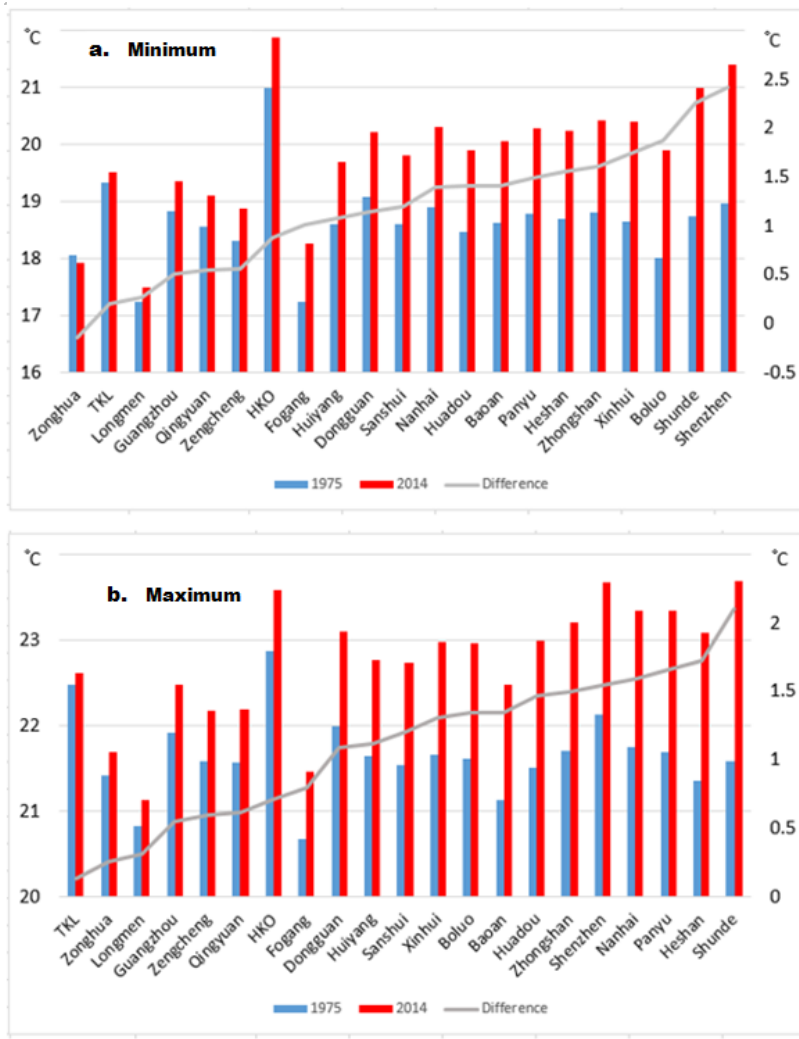
Figure 5. Daily (a) minimum, and (c) maximum temperatures for 1975 and 2014 (left axis). Stations sorted by difference. Right axis and trend line represent absolute difference.

3.2 Relationship between Impervious Surface Area (ISA) and daily T_{min}

Figure 6 illustrates the relationship between changes in T_{min} and ISA for each buffer zone. As seen, the R^2 values of 0.25, 0.18 and 0.20 for the 1, 3 and 5 km buffer zones suggest the relationships are not strong, although some relationship is present, and this is slightly higher in the 1 km buffer zone. The offsets also suggest that an ISA increase of 40% in the 1 km surrounding region is required for any increase in T_{min}, and 27 % and 14% respectively in the 3 km and 5 km regions. To investigate spatial patterns in the T_{min} and ISA changes, Figure 5 shows the spatial distributions of these changes. The greatest T_{min} increases occurred in the southern and south-western parts of PRD, except for the two Hong Kong stations TKL and HKO, which saw only small temperature increases. These two stations also experienced only small increase in ISA.
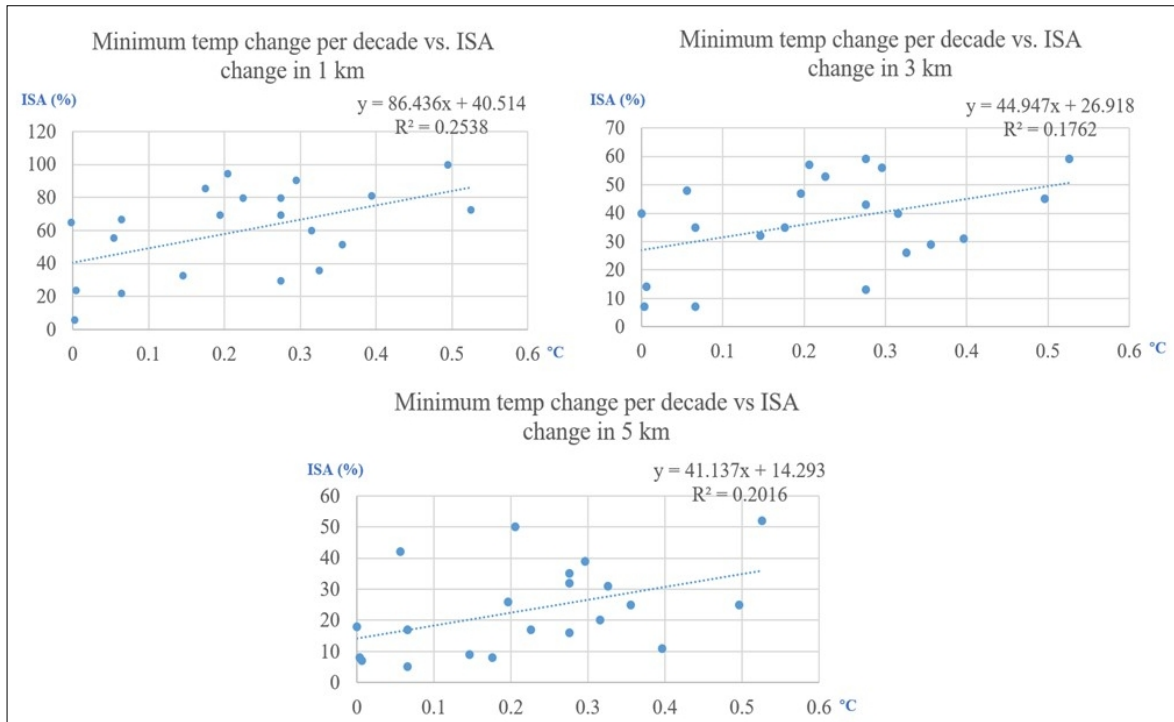
Figure 6. Relationship between changes in T_{min} and changes in ISA from 1975 to 2014 for 1 km, 3 km and 5 km buffer rings.
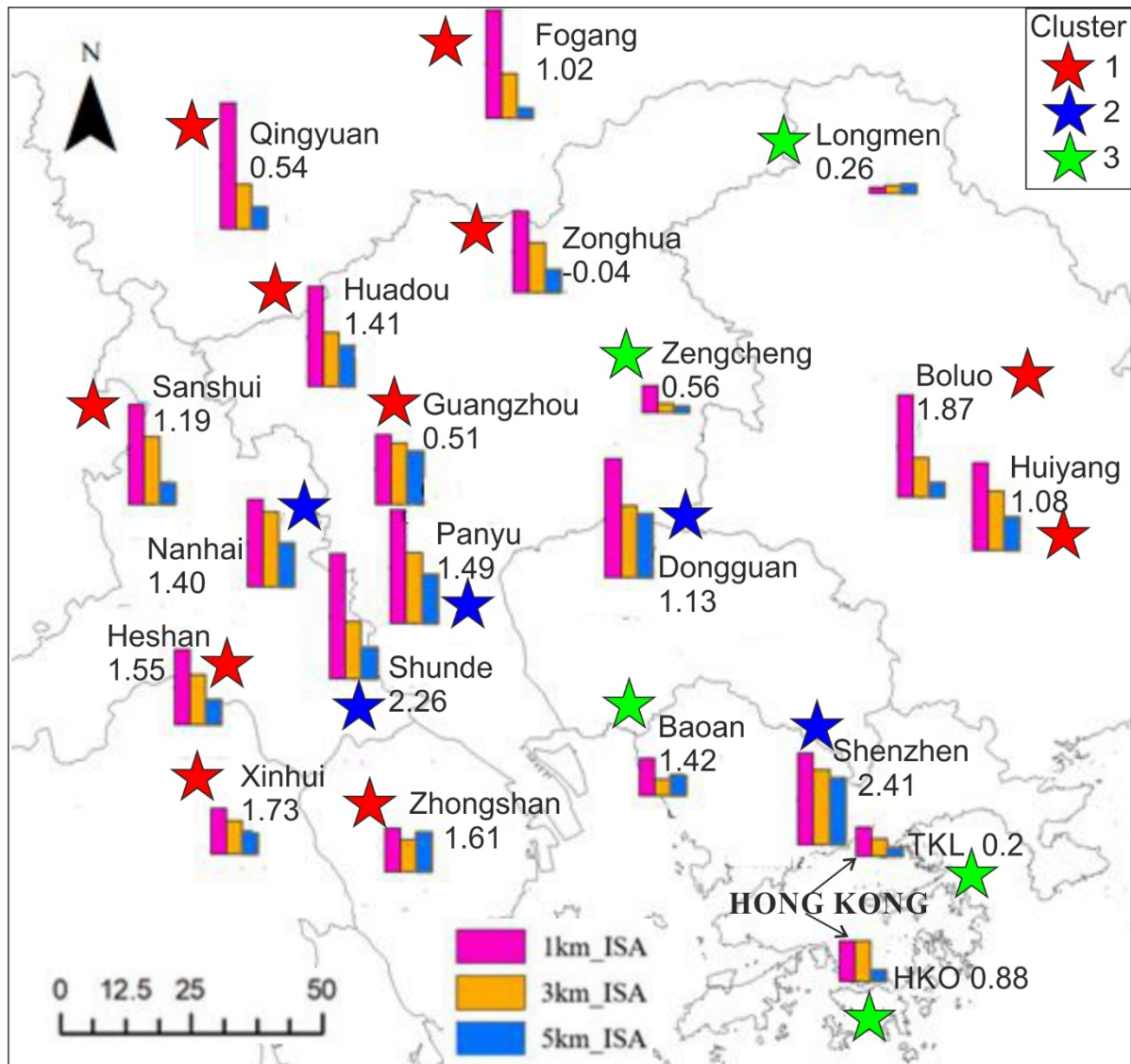
Figure 7. Spatial distribution of changes in ISA and T_{min} (°C) 1975-2014, and distribution of clusters. Red, blue and green stars represent cluster groups 1, 2, and 3 respectively.

3.3 Clustering by magnitude of change in ISA and T_{min}

Because the of the relatively low correlations between changes in T_{min} and ISA for all stations, and the observation (Figure 6) that the minimum percentage of ISA increase required to effect any increase in T_{min}, is 40 %, 18 % and 20 % for the 1, 3 and 5 km buffer rings respectively, the stations were clustered using SPSS. The clusters were determined by changes in T_{min} and ISA change, with % ISA change carrying the heavier weight.

Cluster 1 (red star on Figure 7) refers to cities which had moderate increase of ISA overall. The increase in T_{min} is also generally moderate. The 11 cities in Cluster 1 are Boluo, Xinhui, Heshan, Zhongshan, Huadou, Sanshui, Huiyang, Fogang, Zonghua, Qingyuan and Guangzhou. In these cities the highest increase of ISA is found in the 1km buffer immediately surrounding the station, followed by the 3km, then the 5km buffer. Within this group the average correlation (R^2) between changes in T_{min} and ISA in 1 km buffer zone is 0.27 (Table 2).

Cluster 2 (blue star on Figure 7) refers to cities where the overall ISA increase is high, and also the increase of T_{min} was above the mean for all stations. The 5 cities in Cluster 2 are Shunde, Shenzhen, Panyu, Nanhai and Dongguan. Although Dongguan leads the overall increase in ISA, followed by Shenzhen, Panyu, Nanhai and Shunde, the two highest increases in T_{min} were observed at Shenzhen and Shunde. These stations commenced urban development in the 1980's, and show the highest percentage increase in the 1 km buffer ring. Within this group the average correlation between changes in T_{min} and ISA is R^2=0.51.

Cluster 3 (green star on Figure 7) is the opposite of Cluster 2. It includes cities with low overall increase in ISA, and the increase in T_{min} is below mean compared with other clusters. This cluster comprises Baoan, HKO, Zengcheng, Longmen and TKL. Longmen is the station with the smallest increase in temperature, as well as the lowest ISA increase. Within this group the average correlation ($R^{2)}$ between changes in T_{min} and ISA is 0.26. This low correlation may be because although Longmen, TKL and Zengcheng show low increase in both ISA and T_{min} over the study period, the other two stations, HKO and Baoan have special characteristics. Baoan station is located at Shenzhen's airport, where nearby development is restricted, although both T_{max} and T_{min} have increased by 0.3 and 0.5 °C respectively above the background increase. These increases may be associated with greenhouse gas release from growth in flights and vehicular emissions. At HKO most urban development occurred before the study period, and the moderate temperature increase here may be associated with feedback effects from the region as warming occurred.

Cluster	1 km buffer	3 km buffer	5 km buffer
Group 1. Moderate increase in ISA and T_{min}	0.27	0.29	0.25
Group 2. High increase in ISA and T_{min}	0.51	0.47	0.53
Group 3. Low increase in ISA and T_{min}	0.26	0.16	0.10
ISA% in 2014 and increase in T_{min}	0.13	0.20	0.29

Table 2. Correlation (R^2) between increases in ISA and T_{min} according to cluster grouping of the 21 climate stations based on degree of change.

4. Discussion

The study has observed a fairly weak relationship between increasing temperatures and local urban development represented by ISA, except for the five stations in cluster group 2 (large increase in both ISA and T_{min}) which showed moderate correlation (R^2=0.51, 0.47 and 0.53) in the 1, 3 and 5 km buffers respectively (Table 3). The fact that another 8 stations (a total of 13 out of 21 stations) exceeded the background increase for daily T_{min}, but showed small increase in ISA, suggests the operation of ~~other~~ factors other than local urban development in the immediate surroundings.

The moderate to low correlations overall, may be explained by regional rather than local scale developments, including not only local UHI effects, but also feedback from the urban boundary layer of the wider urbanized Pearl River Delta region. This region has experienced very rapid urban and industrial development over the last four decades, with massive increase in population, transport and buildings. The new developments would increase the regional heat storage capacity, with more long-wave radiation trapped by artificial building materials. Another source of increasing temperatures is the enormous number of factories in PRD releasing heat as a by-product of industry, and particulate emissions which block outgoing radiation during both day and night. As the temperature has been rising, more energy consumed by air conditioning, in turn releases more heat. These factors would create a large

urban boundary layer (UBL) (Oke 1976), covering the whole PRD region including the Pearl River estuary and Hong Kong and Macau on either side. The existence of this UBL is described by Lam et al (2005) and Yang et al (2012) in relation to circulatory feedback of urban pollutants within PRD region, which return to ground level after convectional uplift over warm urban surfaces. Thus heat trapped in the UBL will diffuse across the UBL, and feed back into the Urban Canopy Layer (UCL) where urban structures in any area will reabsorb the heat.

Figure 8 is a MODIS satellite image showing the annual mean of Land Surface Temperatures (LST) across the PRD for 2016. It shows LST at least 10 °C above background rural temperatures over an area of approximately 10,000 km^2, including all PRD cities as one continuous area. In terms of air temperature the UHI has been characterised as a heat dome extending from the surface to the inversion level, or top of the UBL, within which heat disperses over the UCL (Fan et al, 2017). The dome's horizontal diameter is given as 1.5 to 3.5 times the diameter of the urban area. In calm weather conditions, air circulation within the dome is driven by upward flow in the form of turbulent plumes fed by sensible heat flux from the surface. This upward flow over the urban area diverges to outward flow at the upper boundary, and feeds back to the surface at the edge of the dome. This means that as regional urbanisation continues, temperatures within the whole PRD region will probably increase further at individual stations even if there are no further developments in the immediate vicinity. The fact that the largest (5 km) buffer zone had the highest correlations between changes in T_{min} and ISA in cluster group 2 (high increase in both ISA and T_{min}) supports this theory.
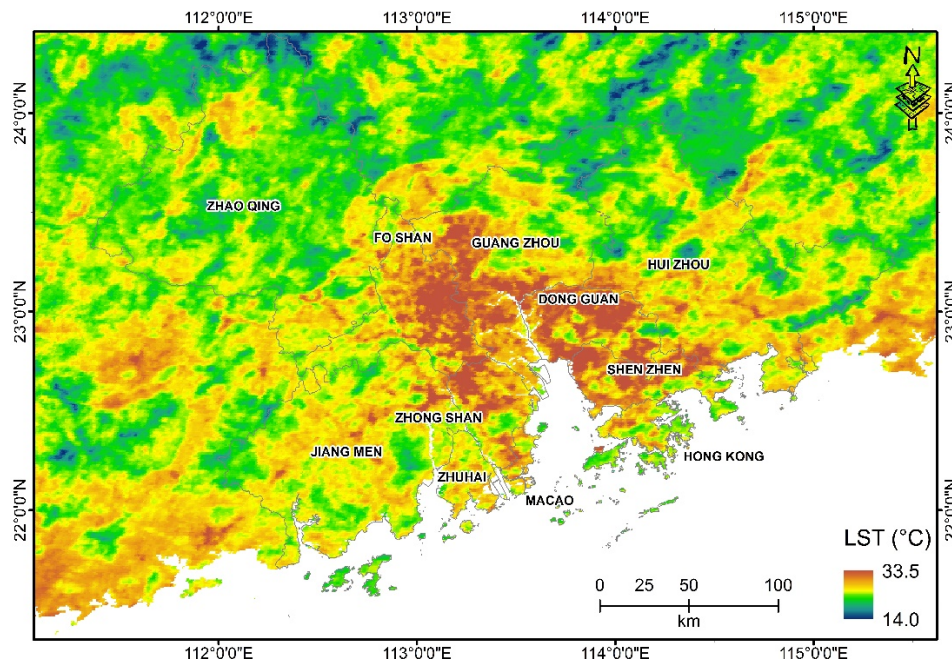

Figure 8. MODIS image of Land Surface Temperature (LST) over PRD, annual average for 2016.

In terms of T_{max}, the fact that 14 out of 21 stations exceeded the background warming rate of 0.9 °C, and seven of these by more than 0.5 °C, is difficult to explain, as T_{max} increase is not generally associated with urbanisation, especially in high rise cities with shaded streets during the day. We have also noted here, that those stations which exceeded the background warming rate for T_{min}, also exceeded for T_{max} increases. However, model simulations over the PRD by Lo et al (2007) showed that urban areas produced higher near surface temperatures

during the daytime as well as at night. They reported high surface energy flux in the afternoon which gives a positive temperature anomaly throughout the Planetary Boundary Layer up to 2 km above the surface. Although Figure 2 indicates that T_{max} in rural areas of Hong Kong can be higher than in urban areas, the data in Figure 2 are for winter, and this agrees with a study of UHI effects on temperatures in UK (Goddard and Tett, 2019) which reported a significant impact on T_{max} only in winter, attributed to anthropogenic heating. But a study of urbanisation effects in China (Ren and Zhou, 2014) reported more significant urbanisation effects on T_{max} in summer, especially in the south of the country, attributed to use of air conditioning. Feng et al (2014) also estimate that anthropogenic heating, has raised T_{mean} in urbanised areas of China by 0.5 to 1.0 °C. In the PRD region, T_{max} above 30 °C for three months as well as high humidity, corresponding to severe stress on the ASHRAE human comfort index, make air conditioning use essential. Air conditioning is also normal in other months when medium or mild climatic stress is coupled with reduced wind speeds and high density, high rise and often poorly ventilated cityscapes.

The study has shown that T_{mean} in the PRD has risen by 1.09 °C over the last 40 years ie. by 0.27 °C per decade, indicating significant urbanisation effects on mean, as well as on maximum and minimum temperatures. This can be compared with IPCC's Fifth Assessment Report (AR5), which did consider UHI effects, but assumed only minor influence on mean global temperatures, citing an estimate of 0.01°C per decade, from UHI effects (Efthimiadis and Jones, 2010). However the report also recognised that UHI influences may be region-specific, and for China as a whole the effects of UHI and LULC change on temperature is estimated in the order of 0.1°C per decade (Yang et al, 2010). The 0.27 °C per decade observed here is almost 3 times this estimate for China as a whole.

As the Hong Kong station at HKO was the only station already built-up before the 1970s, it may be expected to show only changes due to background warming during the study period, unrelated to urban growth. This was indeed confirmed by the observed minor changes in HKO's T_{min} and ISA. In 1975 its high absolute T_{min} values of 20 °C in 1975 was 1.5 °C higher than all 20 other stations (Figure 5a). By 2014, two other stations, Shunde and Shenzhen had caught up to HKO's 1975 T_{min} and several others were similar, confirming the effects of urbanisation.

5. Conclusion

The study shows that T_{min}, T_{max} and T_{mean} have risen significantly over the last four decades, across a large area including all PRD cities, an urbanised area of approximately 52,000 km². The observed effect of urbanisation on T_{max} ~~remains~~ seems somewhat surprising, as most PRD cities are high rise, thus subject to daytime shadowing at street level. However as urbanisation progresses street level warming from air conditioning and vehicular exhausts increases, contributing to increased T_{max} as well as T_{min}. This accords with the circulatory feedbacks over the PRD from warm air uplift over urban surfaces (Yang et al, 2012; Lo et al, 2007), as well as the heat dome circulation model described by Fan et al (2017).

The study indicates that a clear relationship can be demonstrated between local urban development and T_{min} only for locations showing significant urban development ie. stations in cluster group 2 which showed high increase in T_{min} and ISA. At several other sites T_{min} was seen to increase above the background warming rate. This is attributed to regional influences of warm air uplift and subsequent feedback of warm air from the regional UBL into the local UCL, within an urban heat dome. Due to the merging of individual urban

centres (the PRD includes 123 cities of between 1 to 10 million), this heat dome extends across the PRD. Thus as the intensity of the regional UHI increases, and under global warming influences, local temperatures should increase further, even in the absence of further local development, as urban surfaces store the additional heat more efficiently than rural surfaces.

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